A Systems-Driven Approach to Solar Energy R&D

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Abstract – *The Department of Energy (DOE) Office of Solar Energy Technologies uses a systems-driven approach to program management. The approach uses market analysis, modeling, and test and evaluation to prioritize research needs and assess progress. For each target market application, a reference system design is developed. Parametric analysis of the reference design is used to identify technology improvement opportunities that will lead to lower levelized cost of energy. Multiple technology pathways, where appropriate, are used to reduce risk. A formal stage-gate management process is used to determine when research activities should be graduated to the next stage or should be terminated due to insufficient progress.*

Keywords: Solar energy, program management, modeling

1 Introduction

As solar energy applications have moved from space to remote off-grid applications to building rooftops and utility power systems, the focus of research has moved from laboratory devices to components and complete systems. The DOE solar energy program has adopted a systems-driven approach to managing research and development that includes:

- Using market analysis to establish target metrics for supplying energy at a competitive cost
- Developing system models that include all aspects of technology cost and performance
- Establishing reference system designs for target markets
- Identifying specific technology improvement opportunities (TIO's) to increase performance and reliability and reduce cost
- Using parametric analysis to identify the TIO's having the highest impact on cost, performance, and reliability
- Benchmarking cost, performance, and reliability through system and component test and evaluation
- Pursuing multiple technology pathways, where appropriate, to reduce risk
- Applying stage-gate management to evaluation of technology progress

This approach is intended to ensure that solar energy technology will be competitive with conventional energy sources in a wide array of U.S. markets by 2015. The DOE program conducts research in solar energy technologies, including photovoltaics, concentrating solar power, and solar heating and lighting. Due to space limitations, only photovoltaics is used to illustrate the approach in this paper.

2 Market analysis

To make a significant contribution to the nation's energy supply, solar energy must be competitive with conventional energy sources. The Solar Program's economic targets (table 1) were determined based on analyzing Energy Information Administration data for key markets.

Table 1. Solar Program 2015 Targets (¢/kWh) [1]

Market	Residential	Commercial	Utility
U.S. Market Price (2005)	5.8-16.7	5.4-15.0	4.0-7.6
PV Targets	8-10	6-8	5-7

The 2005 market price range estimate for dispatchable utility power (5.6–7.6 ¢/kWh) is based on the Levelized Cost of Energy (LCOE) of new combined-cycle gas turbines in the Southwest United States. Nondispatchable power has a current market price of about 4 ¢/kWh [1]. The target costs for electricity from solar energy represents installations in the Southwest. Installations where solar energy is less plentiful will have higher cost. For example, the solar resource in Chicago is about one-third less than in Phoenix.

3 System model

A system model, called the Solar Advisor Model, has been developed that includes performance, cost, and financial models. The Solar Advisor Model incorporates a user-friendly interface that permits parametric modeling of system and component options. The model uses component performance parameters; component and system manufacturing, installation, installed, operating, and maintenance costs; and financial parameters to calculate energy produced, system cost, and levelized cost of energy. An example of model output is shown in figure 1.

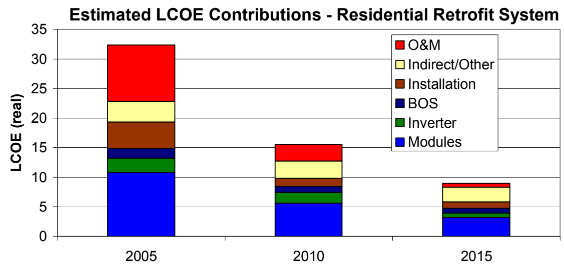

Figure 1. Solar Advisor Model Example Output [1]

The Solar Advisor Model is a work-in-progress. The performance model is based on Sandia's Photovoltaic Array Performance Model [2]. An inverter performance algorithm has been developed for addition to the model. In the most recent release, the capability to analyze tax credits and other incentives has been added to the financial model. Development of detailed cost modeling capability has just begun. In addition to performance and financial algorithms embedded in the model, users can develop submodels as spreadsheets that can be called by the Solar Advisor Model. The latest version of the model may be found at www.eere.energy.gov/solar/solar_america.

4 Reference systems

Photovoltaics is a modular technology, with the smallest element being the PV cell. A factory-produced package containing multiple cells is called a module. In application, modules are mounted on a ground-mounted frame or on a building and wired in series into strings which are in turn wired in parallel to form an array. In a grid-connected system, an inverter is used to convert the dc output of the array to ac power as required by the grid (Figure 2).

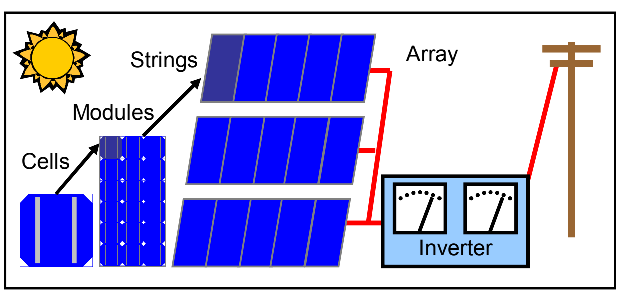

Figure 2. Photovoltaic System Architecture

To provide a baseline for analysis and planning, representative system designs have been identified for each of the target markets. These designs, which we call reference systems, are baseline system designs containing representative components and of a size that address each of the target markets. The baseline characteristics of reference systems represent the current, commercially-available state of the art.

Four reference system designs have been identified for photovoltaic systems. The residential reference system is an array of 40 100W roof-mounted, crystalline silicon modules and a single 4 kW inverter. The commercial reference system is an array of 1,000 150W crystalline silicon modules, roof-mounted on a commercial building, with a 150 kW inverter. The flat-plate utility-scale system is built on the same system configuration as the commercial system, with 67 150kW subsystems combined to produce 10 MW. However, the modules are ground-mounted on single-axis tracking structures. The program also includes a 10 MW utility-scale system composed of two-axis tracking 40kW concentrators. Concentrators use lenses or mirrors to focus sunlight onto high efficiency silicon or multi-junction cells.

5 Technology improvement opportunities

Technology Improvement Opportunities (TIO's) are specific changes that can be made to improve performance, increase reliability, or reduce cost of components and other elements of installed system cost. TIO's are first identified at Tier 1, the highest level, and then are identified in detail at additional levels in a tree-like structure. For photovoltaics, four high-level TIO's have been identified: modules; inverters & other balance-of-system components; systems engineering & integration; and deployment and facilitation. Reference system components provide the baseline relative to which the technology can be improved and analyzed.

PV modules are the highest-cost element of a PV system, and thus are the focus of a significant majority of research efforts. Tier-2 TIO's for modules include absorbers (reducing impurities and defects, thinner wafers, improving hydrogen passivation techniques…), cells and contacts (lower-cost cell processing leading to higher-efficiency devices, novel cell-contacting schemes, novel device structures…), interconnects (improving performance while reducing costs), packaging (innovations to reduce optical losses, lower costs encapsulation materials that maintain reliability, frameless modules…), and manufacturing (pilot-scale processing, scale-up to high-volume processes, process line diagnostics…).

For inverters and other balance-of-system elements, Tier 2 TIO's include inverter software, inverter components and design, inverter packaging and manufacturing, inverter integration (communication protocols…), and other balance-of-system components (structures, trackers, wiring and interconnection…). Balance-of-systems for concentrators also includes the optical components (lenses, mirrors, and structures) as well as thermal-management elements to remove heat from the high-concentration cells.

The system engineering and integration TIO is focused on reducing the installed cost of systems by moving much of the assembly and integration from the field to the factory, and improving quality to reduce maintenance. Tier 2 TIO's include system manufacturing and assembly (standardized component specifications and interfaces, preassembly of modules onto structures that are also shipping fixtures…), and system installation and maintenance (improved, lower-cost installation procedures; development of training and certification programs for installers…).

The deployment facilitation TIO is focused on improving acceptance of PV and eliminating barriers in the market place. A key aspect of this TIO is development and coordination of codes and standards, including updating the PV portion of the national electrical code, and working with utilities and regulatory agencies to develop uniform interconnection standards. The program also provides support to deployment initiatives, and coordinates with state and local programs to increase deployment of PV.

6 Parametric analysis using the solar advisor model

Parametric analysis is used to identify TIO's that have the most impact on system performance, cost, and reliability and is also used to identify TIO's that, while perhaps small in impact, are critical to achieving program goals. For example, significant tradeoffs must be examined within the context of module design and fabrication processes as they relate to the module manufacturing cost parameter alone. Figure 3 displays a set of alternatives within the context of a fixed system design, in which total module manufactured costs must not exceed \$1/Wp (Wp = rated power at design solar input of 1,000 W/m^2) for the module. Within this constraint, a variety of module designs are possible – provided that the lost value from lower module efficiencies is recovered through low manufacturing costs (expressed in \$/m^2 for material and processing). This analysis can therefore be used to inform decisions about the relative process engineering challenges associated with achieving higher efficiencies in a given module manufacturing technique.

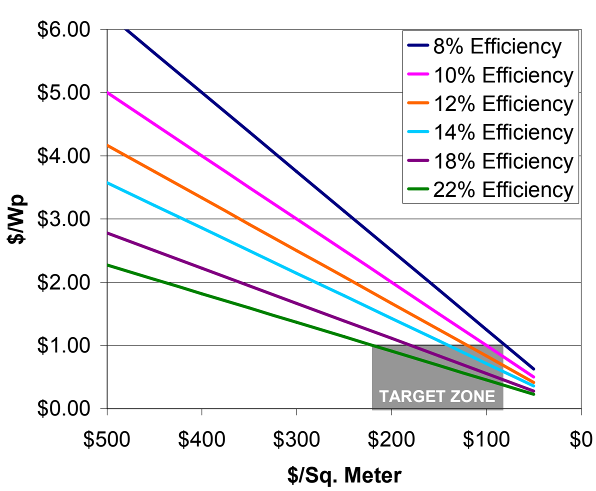

Figure 3. PV Module Cost (\$/Wp) vs. Efficiency and Manufacturing Cost (\$/Sq. Meter)

Historically, module efficiency and manufacturing cost have been the primary metrics used in the PV program. Progress in inverters has also been measured in terms of efficiency and manufacturing cost (\$/Wp). The cost of other balance-of-system components has typically been expressed in terms of \$/m^2, which recognizes that an array of lower-efficiency modules will require more area and thus more support structure than wiring and higher-efficiency modules producing the same power. However, the Solar Advisor Model enables analysis using levelized cost of energy as an overall system metric.

Significant gains in both cell and module efficiency have been achieved, while module manufacturing costs have declined by ~20% each time manufacturing volume doubled (80% learning curve) [1]. Since module costs have dominated system costs, the cost of energy from PV systems has dropped proportionately. However, as the diversity of module technologies, efficiency, and sizes grow, these two metrics are not sufficient to estimate the impact of research on system cost. Furthermore, as the program seeks to achieve competitiveness with conventional technologies, it is important to identify other opportunities for or obstacles to reduction of the cost of energy within the total system design and implementation. For example, monolithic-construction thin-film modules are often relatively small in size, typically 60W, compared to cell-based modules, which are manufactured in sizes as large as 300W. The \$/Wp module manufacturing cost and \$/m^2 metrics suggest that a system composed of 60 W, 10% modules would have the same cost as a system composed of 300W, 10% efficient modules, but clearly more expense is involved in installing 5 times as many modules for the same rated power. As a result, to achieve the same levelized cost of energy, the manufacturing cost of the smaller module must be somewhat lower to achieve the same installed cost.

Similarly, peak efficiency is not an adequate indicator of system performance when different technologies are compared. For example, the effect of temperature on thin-film module performance can be quite different than for crystalline silicon modules. The output of crystalline silicon modules declines as the temperature rises, while the output of some amorphous silicon modules actually increases. Also, the efficiency of some modules may be more sensitive to solar input than is the case for others. Comparing modules by comparing name-plate power ratings is not sufficient. To gain a true understanding of annual performance, the array output must be modeled using annual weather data for the proposed location.

A clear example of the trade-off between design parameters is cost versus expected lifetime for inverters, in particular residential-scale inverters. Large (150kW) inverters in commercial and utility-scale systems have a high unit cost, but lower cost in terms of \$/W$_p$ (~\$0.50-0.60/W$_p$ in 2005) Such large units produce a substantial amount of energy, and occasional maintenance is affordable. In contrast, residential inverters have lower unit cost, but cost ~\$0.90/W_p in 2005. If the inverter is not reliable, the benefit of the relatively small energy output of a residential system could be significantly reduced by service calls or replacement. The Solar Advisor Model was used to compare the tradeoff between inverter life and first-cost, as shown in figure 4. In this analysis, an inverter that costs \$0.80/W_p (\$4,000), and lasts the life of the system (30 years), contributes 2.2¢/kWh to the cost of energy from the system (this figure is for the inverter only, and does not include the cost of modules, other balance of system components, etc.) If the inverter lasts only five years, at which time complete replacement is assumed, then the inverter contributes 8.3¢/kWh to the cost of energy from the system. Another way of looking at this example is that the contribution to the cost of energy is the same (2.7¢/kWh) for a 5 kW inverter with a cost of \$2,400 and a ten-year life as it is for a \$5,000 inverter that lasts 30 years.

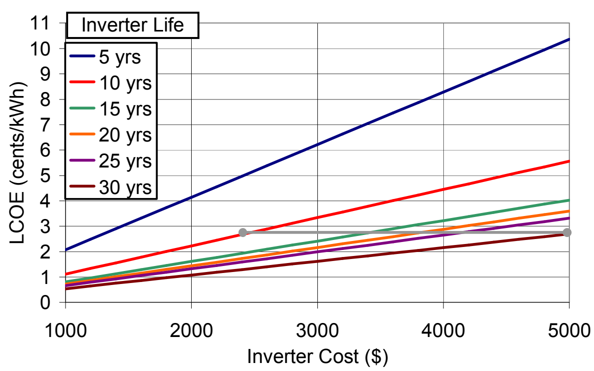

Figure 4. Contribution of 5 kW Inverter to LCOE

Designing a residential inverter that will last 30 years without maintenance is a challenge. Unlike other electronics in a home, such as a microwave, the inverter must operate at high power levels day after day, often mounted outside in heat, moisture, and dirt. Electrolytic capacitors are the primary components that limit inverter lifetimes. Designers are working towards reducing the requirement for capacitance and using longer life, advanced capacitors.

7 Benchmarking

To perform accurate analysis of the cost of energy from systems, to compare the impact of various research options, and to assess progress towards market goals, accurate cost and performance data must be obtained. Benchmarking is used to determine the current state of the art and to assess research progress. Benchmarking includes detailed performance measurements of materials, components and systems; accelerated aging and long-term exposure tests to assess reliability; and due diligence evaluations of manufacturing and installation costs.

As the examples presented above make clear, understanding peak efficiency and manufacturing cost is not sufficient. Scientists and engineers at DOE's national laboratories are developing increasingly sophisticated measurements and are developing increasingly sophisticated algorithms to accurately predict system performance. A protocol for characterizing module performance has been developed, and a large number of modules have been characterized. An algorithm that uses this data is part of the Sandia Photovoltaic Array Performance Model [2], which has been validated against measured data on systems installed in Albuquerque. The data and the algorithm are accessible within the Solar Advisor Model.

An inverter model has also been developed that has been shown to accurately predict inverter performance [3]. Coefficients for this model can be developed from existing California Energy Commission data sets [4]. This new inverter model will replace the single-point efficiency value used in the current version of the Solar Advisor Model.

Additional efforts are underway to validate the system performance model, as encoded in the Solar Advisor Model, as well as other publicly-available performance models, by comparison to the performance of several systems installed in Albuquerque. As performance data is collected on additional systems, model validation will be extended to additional technologies and locations.

A contract has recently been placed with Navigant Consulting, a company with extensive experience in conducting due diligence estimates of manufacturing costs. Navigant will be working with PV companies who are conducting research supported by DOE to develop detailed manufacturing cost models for a range of PV technologies. The model will evaluate the effect of a range of parameters, such as manufacturing site (labor and utility costs), material parameters (cost and properties), equipment parameters (speed, cost, capacity), design parameters (device yield, size, and efficiency) and factory parameters (volume and number of shifts). A system cost model will also be developed, building on work previously performed at the National Renewable Energy Laboratory (NREL). Both of these cost models will be built within spreadsheets so that they can communicate with the Solar Advisor Model. Manufacturing process research, whether performed by industry companies or supporting universities, should be informed by the development of these types of manufacturing cost models to assure that the process parameters being targeted for improvement will, in fact, result in cost reductions commensurate with the cost of research.

8 Multiple technology pathways

For critical, high-risk system elements, pursuing multiple development pathways helps ensure a successful outcome. Crystalline silicon continues to be the dominate technology for PV modules. Industry has continued to improve efficiency and reduce manufacturing costs, in part by using thinner wafers. In the last two years, however, high demand and constrained supply of the silicon feedstock has led to higher prices. While prices are expected to decline as increased silicon feedstock capacity comes on-line, development of alternative technologies continues. Thin-film technologies offer the potential of lower cost because the deposition processes used to produce these films require significantly less material than wafer-based crystalline silicon devices. Amorphous silicon and cadmium telluride devices are in full commercial production. Production of CIGS modules is occurring at a lower level. In addition, scientists in industry, in universities, and at NREL are developing novel materials, such as organic PV devices, that have the potential for even lower cost.

Another approach to reducing cost is using concentrating optics to decrease the amount of semiconductor area required. This approach trades off the cost of semiconductors versus the cost of optics, tracking structures, controls, and associated O&M requirements. Since minimal semiconductor area is required, higher-cost, high-efficiency devices, including both silicon and multi-junction cells, are used. Because concentrators can only focus direct sunlight, they are most suited to application in the sunny Southwestern United States. Most concentrators are large, and the target market for these systems is utility-scale systems where large numbers of systems can be grouped together to minimize O&M costs.

A variety of approaches to inverters are also underway. Small residential systems typically have a single inverter, but, in large commercial and utility-scale systems, system designers may use multiple smaller inverters or just one or more larger inverters. Another approach to inverters is the module-scale inverter. In this approach, a small inverter (200-300W) is placed on each module. There are a number of benefits to this approach, including elimination of dc wiring and single-point failures, and increased manufacturing volume of a single size of inverter, rather than requiring multiple inverter sizes for a range of system sizes. This approach also introduces design flexibility. In a conventional array, if one module or string receives less sun than another, for example due to shading, interactions between the modules and between the strings and the inverter can disproportionately reduce the output of the entire system. In contrast, ac modules operate independently. Shading of one module does not affect the others, and modules can be placed on different roof surfaces, such as south and west facing. Also, more modules can be added at any time with only addition of wiring, and not a new or larger inverter.

9 Stage-gate management

The solar program is employing a stage-gate management process to ensure adequate progress is verified at each step of development before investing in the next development step, as shown in figure 5. The first step in the process, *materials and device concepts*, is basic research funded by the Department of Energy's Office of Science in response to proposals (gate 1).

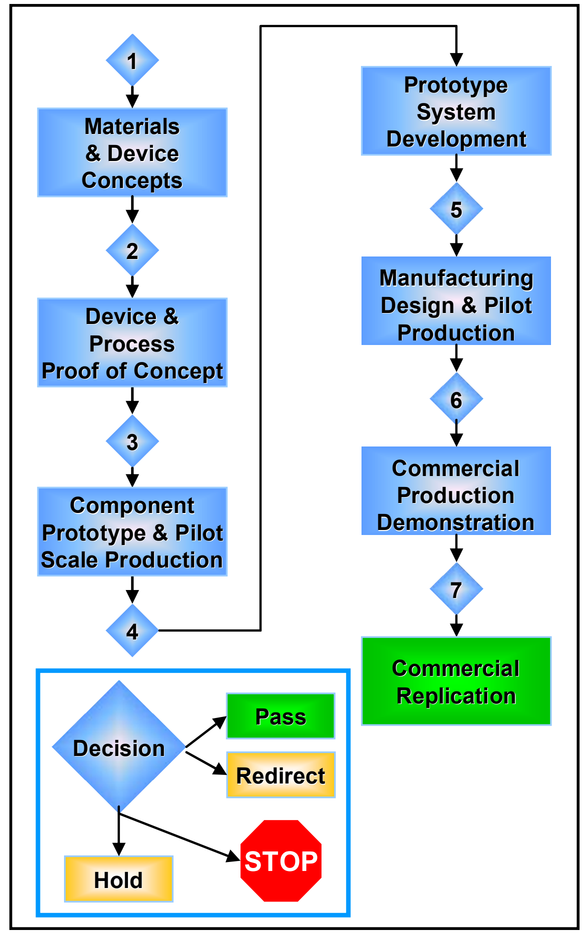

Figure 5. Stage Gate Review Process

The Solar Energy Technology Program is an applied research program, and all research activities must be pursued with the ultimate program goal firmly in mind. Initial development activities within the program include development of devices and proofs of concept. Activities at this stage tend to be small, high-risk exploratory projects, such as the development of novel devices using materials discovered through basic research or pursuit of new ideas resulting from innovation or technology assessment. Reducing uncertainty regarding material performance, reliability, and cost are key outcomes of this stage. As research progresses, analysis of potential outcomes must be more certain and the emphasis shifts towards manufacturing processes and ultimately towards commercialization and deployment. Much of the work at the early stages is done in universities and national laboratories, with minimal requirements for cost share. In later stages, industry involvement and requirements for cost share increase, until commercial replication is achieved.

At the end of each stage, progress is assessed at formal gate reviews through benchmarking and analysis of progress towards program goals. Four decisions are possible as outcomes from a gate review: Pass (to the next stage), Recycle/Redirect (stay in the same stage but complete additional necessary work), Hold (suspend DOE support for the project until additional data supports restarting or canceling), or Stop (no further DOE support for this project).

10 Application

This systems-driven approach is being applied to management of the $148 million dollar Solar America Initiative, which is part of President Bush's Advanced Energy Initiative. A recent Solar America Initiative procurement focused on the development of Technology Pathway Partnerships to develop components, systems, manufacturing, and marketing volume that will meet the program's 2015 goals. Applicants were trained in the use of the Solar Advisor Model and directed to use it in estimating the benefits of their proposed research activities relative to their current, baseline technology. Applicants were also directed to identify stage-gates and corresponding metrics and deliverables to permit evaluation of progress toward goals before additional funds are obligated each year. Awards to these partnerships were announced in March as the first phase of three, 3-year phases.

11 Needs for further work

While the DOE has achieved major advances in the state-of-the-art for PV systems engineering in recent years, there is still opportunity for significant improvements to the analytical methods and software tools applied to the challenges of PV system design. For example, while the DOE's Solar Advisor Model allows designers to evaluate the impact of various system design parameters and costs on the overall levelized cost of energy, the model does not currently provide any optimization function. The same can be said for other commercial software tools, such as Maui Solar Energy Software Corporation's PV Design Pro. Both tools require their user to have sufficient expertise to select components and system designs that will yield a global optimum for the system's requirements. A superior tool would include an optimization sub-routine that could propagate a variety of system configurations through the cost/performance assessment algorithm and return an optimal design. Tools with this type of functionality are prevalent in the aerospace sector, for example, but have not been developed for the PV sector. Similar functionality could also be incorporated into the module manufacturing cost tools that are used to inform process R&D and statistical process controls. Similarly, system performance models such as Sandia's Photovoltaic Array Performance Model do not provide PV system installers and designers with an automated design feedback loop that mitigates the effect of different system designs on system-level efficiencies losses that result from wire selection, shading, or other related parameters. As the market for PV installations grows, there will be a growing need for tools that support rapid, automated PV system design for installers that are new to the practice. University researchers and industry analysts that have expertise in systems analysis could achieve a significant impact on the industry by providing this type of capability.

12 Conclusion

Use of the systems-driven approach and all of its elements will ensure that the Solar Energy Technologies Program is taking an optimum path towards achieving its goals. Continued modeling and evaluation of progress at the materials, components, and systems level enables the program to focus on the most promising research while scaling back or terminating research for which an outcome that meets program goals appears less promising. This approach also helps identify technologies that are achieving full and competitive commercial status and no longer require federal research support.

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